A New Pumping Strategy for Petroleum Product Recovery from Contaminated Hydrogeologic Systems: Laboratory and Field Evaluations

by Abdul S. Abdul

Abstract

More than 200,000 gallons of automatic transmission fluid (ATF) leaked from an underground storage tank system and contaminated an area of about 64,000 ft^2 of a soil and ground water system. A pumping strategy for improved drainage and recovery of free oil was developed, tested in a laboratory model aquifer, and implemented and evaluated at the field site. This pumping strategy differs from conventional approaches in two important ways: (1) The oil recovery rate is carefully controlled to maximize the pumping rate while maintaining continuity between the oil layer in the soil and the recovery well, to avoid isolation of the oil in the subsurface; and (2) The rate of ground water pumping is controlled to maintain the depressed oil/water interface at its prepumped position. This approach prevents further spread of oil into the ground water, prevents reduction in the volume of recoverable oil due to residual retention, and maintains a gradient for oil flow toward the recovery well. In a model aquifer study, nearly 100 percent of the recoverable volume of ATF was pumped from the system, and about 56,000 gallons of the ATF has been recovered from the field site.

Introduction

In a previous study (Abdul et al. 1990) it was estimated that about 208,000 gallons of automatic transmission fluid (ATF) leaked from an underground storage tank system and spread through an area of 64,000 ft^2 of the soil and ground water system beneath a manufacturing facility (Figures 1 and 2). The recovery of free product by pumping is being used as a first step to remediate this site. This paper presents performance results of a pumping strategy for recovery of the free ATF at the contaminated site.

Commonly used product recovery strategies include one or more of the following methods: (1) skimming the free product from a recovery well (product skimming); (2) pumping of ground water to create a deep drawdown cone [illegible] to induce the flow of product to a recovery well (total fluid recovery); and (3) intercepting the product in a trench or drain constructed downgradient of the zone of free product. These methods could have severe limitations for the recovery of viscous fluids, such as ATF, from soil and ground water systems.

The thickness of the oil layer in a well that is open to a zone of free oil depends on the capillary properties of the soil, the density of the oil, and the thickness of the layer of free oil in the soil (Abdul et al. 1989, Farr et al. 1990, Lenhard and Parker 1990). The weight of the oil column in the well is supported by the surrounding ground water that it has displaced. Consequently, the displaced water is under stress and will simultaneously rise as oil is removed from the well, reducing the magnitude of the induced stress. As the oil is removed from the well, a fluid potential is created for both water and oil to flow from the surrounding porous medium into the well. However, the rates of flow of water and oil are inversely related to their viscosities, and because ATF is at least 60 times more viscous than water, the ground water could replace the ATF in the well and eventually isolate it from the recovery well (Figure 3). It follows, therefore, that oil skimming alone, without ground water pumping, could lead to the isolation of viscous oils from recovery wells.

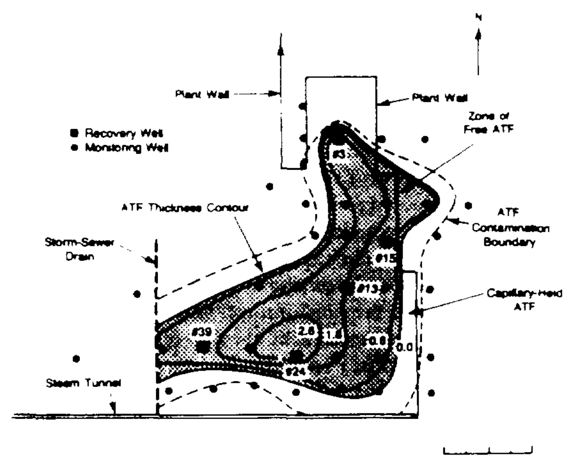
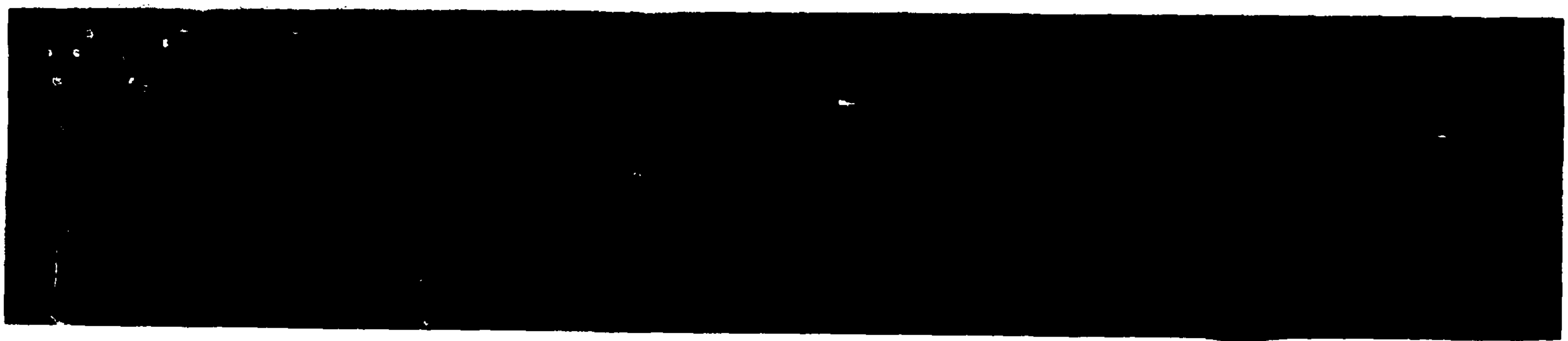


Figure 1. Lateral spread of ATF and contours of ATF thickness in feet (2.6, 1.6, 0.6, and 0.0) before the start of product recovery.



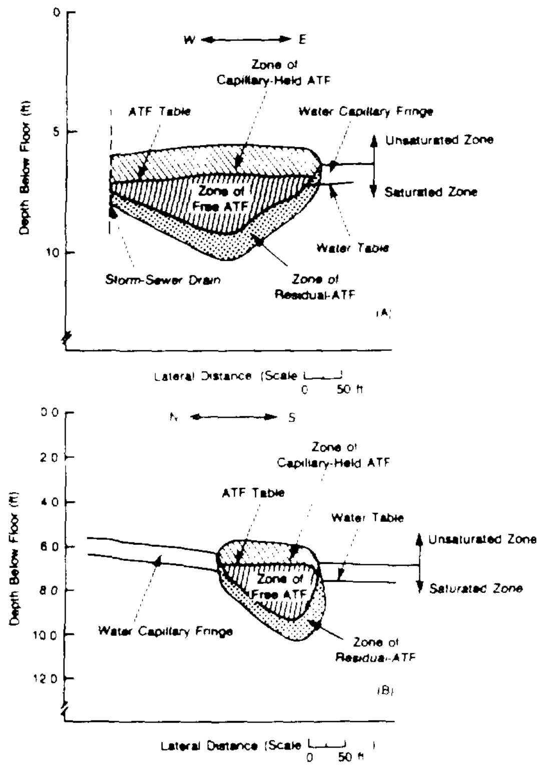


Figure 2. Two vertical sections through the ATF plume.

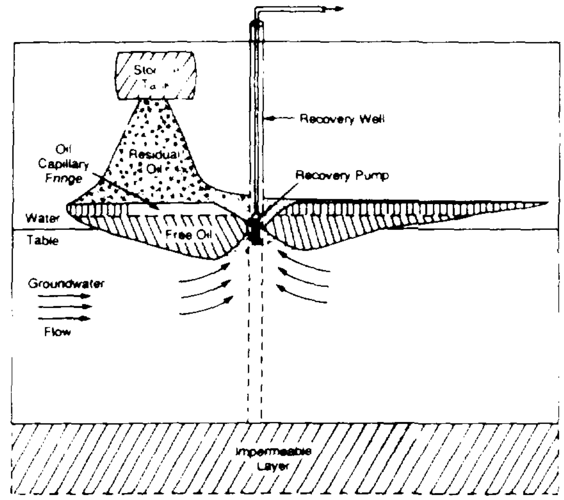


Figure 3. Oil isolation from a recovery well being skimmed to recover the free oil.

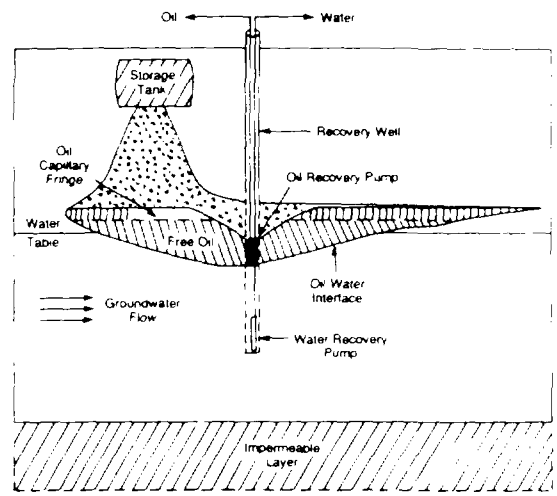


Figure 4. Controlled drawdown of the water table during oil and water recovery.

It is common practice to rapidly pump a well installed through the ground water zone to create a deep drawdown cone and induce the flow of free product to the well. During the development of this cone, the free product will spread downward to ultimately establish new steady-state conditions in the region of the surface of the drawdown cone. This approach could have several disadvantages. First, the oil is spread to deeper and more extensive regions of the subsurface. Second, a large volume of the oil will remain as residual retention in the new regions of contamination, significantly reducing the volume of product available for recovery. Third, treatment of a large volume of contaminated ground water may be required.

Another approach uses a product recovery pump in combination with a water-table drawdown pump. While this approach has advantages of developing a strong gradient for product flow toward the recovery well and separately removing oil and water, it suffers from the same disadvantages described previously for the total fluid recovery approach.

Using drains and trenches for the recovery of oil could suffer from the same limitation of a recovery system, in that these methods could also lead to isolation of the oil. In addition, one trench or drain downgradient of a viscous oil plume would require excessively long travel times for the oil to flow to the receptor and therefore result in poor oil recovery.

The aforementioned limitations can be minimized if a product recovery strategy is developed to prevent isolation of the oil from the well and restrict the spread of oil to previously uncontaminated zones. Such a strategy was developed, based on the use of recovery wells, each having a product recovery pump and a water recovery pump (Figure 4). This approach involves the removal of free product from the well at a rate that maintains a layer of product in the well which forms a continuous layer with the free-oil zone in the adjacent porous medium. As the oil/water interface in the well starts to rise when oil is removed from the well, ground water is pumped at a rate sufficient to maintain the oil/water interface in the well and the porous medium at its original position. While this approach will create a gradient for the oil to flow toward the well, it will also restrict the development of a deep drawdown cone and the further vertical spread of oil.

The performance of the proposed product recovery strategy was evaluated in a laboratory model aquifer and in the field at an ATF-contaminated site described by Abdul et al. 1990.

Study Approach

Laboratory Model Aquif

The model aquifer is 5
feet (140cm) high by 0.33
of Plexiglas (Figure 5)
clean "play sand" that was
a 0.02-inch (0.05cm) stand
a uniform porous mediu
the model in increments
and each new layer was
by using an electric blen
shaft.

One face of the mo
with 26 tensiometers (T
measuring the fluid pr
Each tensiometer has a t
measuring port connected
ter, and a port for flushing
toring system (Abdul et
was separated from the sa
nylon membrane in the
0.00315-inch (80μm) nylo
zone. These membranes
saturated with either ATF
suction head expected du
of the medium was a 2.36
reservoir. These two rese
base by a 0.49-inch I.D.
to maintain constant head
medium. A 1.97-inch I.D.
eight 0.098-inch slots in
through the center of th
packed with sand. Likewis
monitoring wells (MW
installed in the model aqui
ing wells were first mach
and the rectangular side
to the inside surface of th
it possible to observe th
monitoring wells.

The water table was m
33.46 inches (75 and 85cm
aquifer, and the capillary
inches (20cm) above the
pressure relationship for
was determined in funne
From those experiments,
lary fringe under conditio
(33.0cm) for water and 7
and for wetting conditions
3.15 inches (8.0cm) for wa
hydraulic conductivity (K
in column tests using fal
niques (Freeze and Cherr
ured in situ by performing
of the model aquifer (Kri
The values for K, from th
0.047 to 0.118 inch/min (0
from pumping tests range
min (0.01 to 0.02 cm/min

Study Approach

Laboratory Model Aquifer

The model aquifer is 5.91 feet (180cm) long by 4.59 feet (140cm) high by 0.33 feet (10cm) wide and made of Plexiglas (Figure 5). The model was packed with clean "play sand" that was air-dried and sieved through a 0.02-inch (0.05cm) standard mesh sieve. To construct a uniform porous medium, the sand was poured into the model in increments of 0.33-foot thick (10cm) layers, and each new layer was mixed with the previous layer by using an electric blender equipped with an extended shaft.

One face of the model aquifer was instrumented with 26 tensiometers (T-1 through T-26 in Figure 5) for measuring the fluid pressure in the porous medium. Each tensiometer has a fluid chamber and two ports: a measuring port connected to an ATF or water manometer, and a port for flushing entrapped air from the monitoring system (Abdul et al. 1989). The fluid chamber was separated from the sand by a 0.00079-inch (20µm) nylon membrane in the unsaturated zone and by a 0.00315-inch (80µm) nylon membrane in the saturated zone. These membrane sizes were selected to remain saturated with either ATF or water under the range of suction head expected during the study. On each end of the medium was a 2.36-inch wide (6.0cm) boundary reservoir. These two reservoirs were connected at the base by a 0.49-inch I.D. (1.2cm) tube, which was used to maintain constant head conditions on the sides of the medium. A 1.97-inch I.D. (5.0cm) recovery well, having eight 0.098-inch slots/inch of length, was installed through the center of the model aquifer before it was packed with sand. Likewise, three 1.0-inch I.D. (2.5cm) monitoring wells (MW1, MW2, and MW3) were installed in the model aquifer (Figure 6). These monitoring wells were first machined into longitudinal halves, and the rectangular side of the half well was attached to the inside surface of the Plexiglas. This design made it possible to observe the thickness of fluids in these monitoring wells.

The water table was maintained between 29.53 and 33.46 inches (75 and 85cm) above the base of the model aquifer, and the capillary fringe extended about 7.87 inches (20cm) above the water table. The saturation-pressure relationship for water or ATF and the sand was determined in funnel experiments (Abdul 1988). From those experiments, the vertical extent of the capillary fringe under conditions of drainage was 12.99 inches (33.0cm) for water and 7.09 inches (18.0cm) for ATF, and for wetting conditions was 5.91 inches (15.0cm) and 3.15 inches (8.0cm) for water and ATF, respectively. The hydraulic conductivity (K_s) of the sand was measured in column tests using falling- and constant-head techniques (Freeze and Cherry 1979), and it was also measured in situ by performing a constant-rate pumping test of the model aquifer (Kruseman and de Ridder 1970). The values for K_s from the column tests ranged from 0.047 to 0.118 inch/min (0.12 to 0.30 cm/min), while K_s from pumping tests ranged from 0.0045 to 0.0090 inch/min (0.01 to 0.02 cm/min). The porosity of the medium

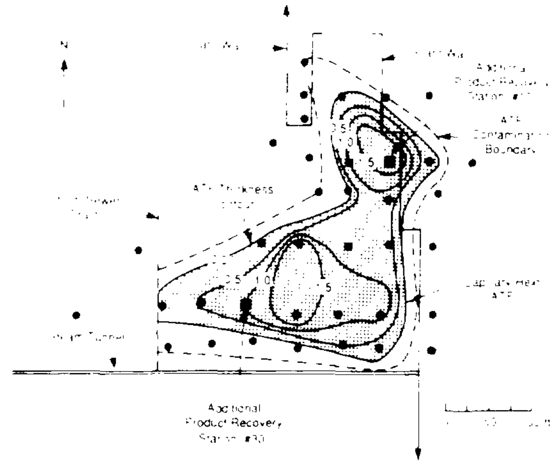


Figure 5. Schematic of model aquifer.

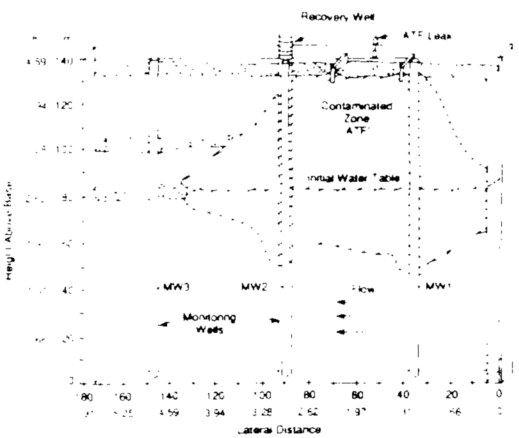


Figure 6. Lateral and vertical distribution of ATF through the model aquifer.

was about 0.40, and the particle density was 159 lb/ft^3 (2.55 g/mL). Ground water discharge was maintained at 0.061 inch^3/min (1 mL/min) in the direction shown in Figure 6. This resulted in an average linear pore-water velocity of 0.078 inch/min (0.20 cm/min).

A total of 3.04 gallons (11.51 L) of ATF was leaked to the surface of the sand, at the location shown in Figure 6, at an average rate of 0.392 gal/day (1.48 L/day) for 7.75 days. The ATF spread laterally and vertically through the unsaturated zone and the capillary fringe, and it subsequently developed a layer of free ATF in the capillary fringe. As the thickness of the layer of free ATF increased and the pressure in the oil layer progressively exceeded the pressure in the surrounding water by the value of the capillary pressure across the ATF/water interface, the ATF/water interface was displaced progressively deeper into the saturated zone. During this vertical displacement, the ATF was also spreading laterally through the capillary fringe. These experimental observations of oil spreading through the unsaturated and saturated zones are consistent with previous observations and discussions of the spreading process (van Dam 1967, Schwille 1967, Abdul 1988). When the distribution of ATF through the system was no longer changing significantly, the ATF had spread through about 33 percent (2.50 cu ft; 70.8 L) of the model aquifer and had formed a 4.27-foot (1.30m) long by 0.26-foot (0.079m) thick layer of free product. The average thickness of the zone of free ATF in the model aquifer was determined by using an ultraviolet "black light" source to locate the zone of highest saturation and by using the ATF manometers to locate the region of that zone where the fluid pressure was higher than atmospheric pressure.

On the average, the volume of ATF in the free ATF zone was the same as that in the ATF fringe zone (0.98 gal; 3.71 L). Of the remaining 1.08 gallon (4.09 L) of ATF, about 0.13 gallon (0.49 L) was stored in the wells and 0.95 gallon (3.60 L) was held in the funicular and pendular zones. This gives an average ATF saturation in the funicular and pendular zones of 24 percent, which compares favorably with the range of residual saturation (20 to 35 percent) measured in funnel experiments. Of the 1.96 gallons (7.42 L) of ATF in the zone of free product and the ATF fringe zone, about 1.37 gallons (5.19 L) could be drained and recovered by pumping, assuming that the remaining 30 percent (0.59 gallons; 2.22 L) would be held in the soil pores as residual retention. The evaluation of the recovery system was to be based on the extent of removal of the 1.37 gallons (5.19 L) of drainable ATF from the zone of free ATF and the ATF fringe zone.

Field Site

The field site is under a manufacturing plant, and it is part of a shallow, sandy ground water system that extends to a clay layer at a depth of about 13 feet (3.96m) (Abdul et al. 1990). The position of the water table is approximately 6.5 feet (1.98m) below the plant floor and fluctuates as much as 2 feet (0.61m) annually. The saturated zone is made up of medium-fine sand. At a porosity of 0.40, an average value of hydraulic conductivity of 0.061 inch/min (0.155 cm/min), and a hydraulic gradient of 0.0025 obtained from flownets for the site, the rate of ground water flow is about 17 ft/yr (5.18 m/yr). The saturation-pressure relationships for ATF or water and material from the site are similar to those for the sand in the model aquifer, having equivalent values for residual saturation and the thickness of the capillary fringe (Abdul et al. 1990).

The contaminated zone occupies an area of about 64,000 ft^2 (5946 m^2) and contains about 208,000 gallons (787,280 L) of ATF (see Figure 1). About 133,000 gallons (503,405 L) of ATF occurs as free product, 50,600 gallons (191,521 L) located in the fringe and funicular zones, and 24,500 gallons (92,733 L) is trapped as residual saturation in the saturated zone beneath the zone of free ATF. Based on a residual retention of 30 percent, the amount of recoverable ATF from the zone of free ATF and from the fringe and funicular zones are 93,000 (352,005) and 35,000 gallons (132,475 L), respectively. It is hoped that this combined volume of ATF (128,000 gallons; 484,480 L) can be recovered from the site by pumping.

Forty-one monitoring and recovery wells were installed at the site (Figure 1). The recovery well (combination well) was specially designed to separately pump ATF or water from the system (Figure 7). The combination well is essentially two off-centered wells: a 2-inch (5.08cm) O.D. inner well and a shallower 4.5-inch (11.43cm) O.D. outer well. Typically, the inner and outer wells are 13 and 11 feet (3.96 and 3.35m) deep, respectively. The two wells are hydraulically isolated from each other to prevent fluid from flowing from one well to the other. Each well is opened to the surrounding medium through the screened section, which consists of parallel 0.01-inch slots (six slots/inch). Typically, the outer well is opened to the medium from 2 feet (0.61 m) above the position of the unstressed water table to 4 feet (1.22m) below the water table (through the zone of free ATF), while the inner well is opened to the next 2 feet (0.61 m) of the saturated zone below the outer well. An air-lift pump in the outer well was used to recover the free ATF, while an air-lift pump in the inner well was used to pump ground water from below the ATF layer and to maintain the ATF/water interface at its pre-pumped position.

Five recovery systems were installed at the site at the locations shown in Figure 1. The number and location of the recovery systems were determined based on pumping test results and mathematical simulations of the water-table response to different pumping strategies. The on/off cycles of the pumps were automatically controlled by presetting their refill and discharge times. In addition, the on/off cycle of the water pump was controlled by a down-well bubbler sensor. A 2-inch-I.D. (5.08cm) monitoring well was installed within 10 feet (3.05m) of each recovery well to provide information on the response of the ATF/water interface and on product thickness adjacent to the recovery well during pumping. Pumping conditions were adjusted to maintain the

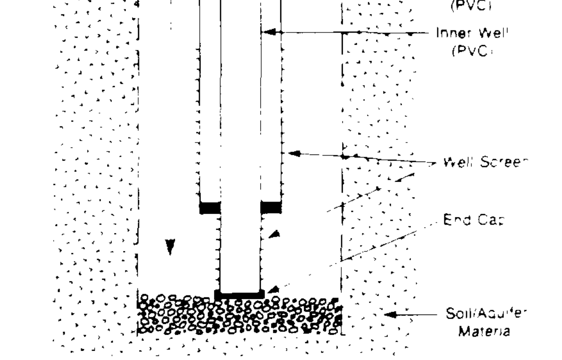


Figure 7. A schematic of well construction and installation.

oil/water interface at its pr
maintain continuity of the A
uct in the medium with the
well.

Results and Discussion

Results from the mode
include the response of pro
toring well located adjacen
the rate of recovery and a
the results from pairs of r
at the field site are simil
recovery systems wi' e p
three systems will be sun

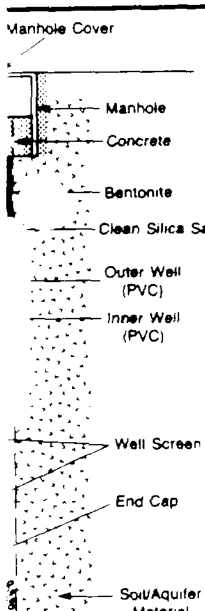
Laboratory Model Aquif

The recovery well in
instrumented with two rec
of the well to pump water f
the other located within th
recover the ATF (Figure
was fitted through a ping-p
end of the tube floats just
in the recovery well. The
adjusted to maintain a colu
the lower 1-inch (2.54cm) s
tube was screened to make
from the base of the well. I
gradually increased over t
recovery, after which the r
gal/min (350 mL/min) to m
face at approximately 1.80
of the model aquifer. This
pumped position of the
medium at MW2 (Figure 6)
from the recovery well wa
wells. The ATF recovery
31 days of pumping becau
99 percent of the fluid be
recovery tube was water.

The heights of water
wells above the base of th
ured at least once daily on w
period. During the leak
located adjacent to the zor
steadily to a maximum va
the day the leak was stopp
thickness in MW2, locate
and adjacent to the recover
ness observed in MW1, bu
tinued to increase, during
leak was stopped, to a r
(0.52 m). Subsequently, the
toring wells decreased as
capillary fringe. About
stopped, and just before th
from the base of the mode
air interface in MW1 was
0.83 m), respectively, and r
(0.46 and 0.86 m), respecti
0.83 feet (0.25 m) in MW
MW2

covery well (combi-
to separately pump
ıre 7) The combina-
ered wells; a 2-inch
shallower 4.5-inch
. the inner and outer
35m) deep, respec-
ıy isolated from each
ıg from one well to
to the surrounding
on, which consists of
nch). Typically, the
from 2 feet (0.61 m)
water table to 4 feet
ough the zone of free
ed to the next 2 feet
w the outer well. An
used to recover the
ı the inner well was
below the ATF layer
interface at its pre-

stalled at the site at
ı mber and loca-
k ıned based on
ıtical simulations of
t pumping strategies.
e automatically con-
d discharge times. In
ater pump was con-
ensor. A 2-inch-I.D.
talled within 10 feet
provide information
ıterface and on prod-
ry well during pump-
ısted to maintain the



ıction and installation.

oil/water interface at its prepumping position and to maintain continuity of the ATF in the zone of free product in the medium with the ATF column in the recovery well.

Results and Discussion

Results from the model aquifer and the field site include the response of product and water in the monitoring well located adjacent to each recovery well and the rate of recovery and accumulation of ATF. Because the results from pairs of recovery and monitoring wells at the field site are similar, only the results from two recovery systems will be presented. Results for the other three systems will be summarized.

Laboratory Model Aquifer

The recovery well in the model aquifer system was instrumented with two recovery tubes: one at the bottom of the well to pump water from the saturated zone, and the other located within the ATF layer to separately recover the ATF (Figure 8). The ATF recovery tube was fitted through a ping-pong ball such that the intake end of the tube floats just below the air/ATF interface in the recovery well. The rate of ATF removal was adjusted to maintain a column of ATF in the well. Only the lower 1-inch (2.54cm) section of the water recovery tube was screened to make sure that water was pumped from the base of the well. The water pumping rate was gradually increased over the first five days of product recovery, after which the rate was kept at about 0.092 gal/min (350 mL/min) to maintain the ATF/water interface at approximately 1.80 feet (0.55m) above the base of the model aquifer. This level approximates the prepumped position of the ATF/water interface in the medium at MW2 (Figure 6). The water that was pumped from the recovery well was returned to the boundary wells. The ATF recovery system was stopped after 31 days of pumping because, at that time, more than 99 percent of the fluid being pumped from the ATF recovery tube was water.

The heights of water and ATF in the monitoring wells above the base of the model aquifer were measured at least once daily on weekdays during the recovery period. During the leak, the ATF thickness in MW1, located adjacent to the zone of the ATF leak, increased steadily to a maximum value of 2.23 feet (0.68m) on the day the leak was stopped. The increase in the ATF thickness in MW2, located downgradient of the leak and adjacent to the recovery well, lagged the ATF thickness observed in MW1, but the thickness in MW2 continued to increase, during the next 12 days after the leak was stopped, to a maximum value of 1.71 feet (0.52m). Subsequently, the ATF thickness in both monitoring wells decreased as the ATF spread through the capillary fringe. About 45 days after the leak was stopped, and just before the start of pumping, the height from the base of the model to the water/ATF and ATF/air interface in MW1 was 1.91 and 2.72 feet (0.58 and 0.83m), respectively, and in MW2 was 1.51 and 2.81 feet (0.46 and 0.86m), respectively. The ATF thickness was 0.81 feet (0.25m) in MW1 and 1.30 feet (0.40m) in MW2.

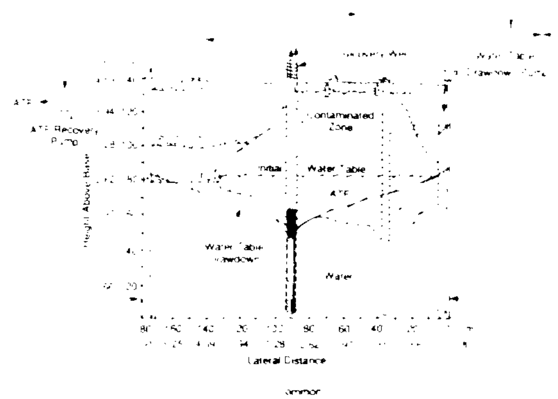


Figure 8. ATF and water recovery system used in the laboratory model aquifer.

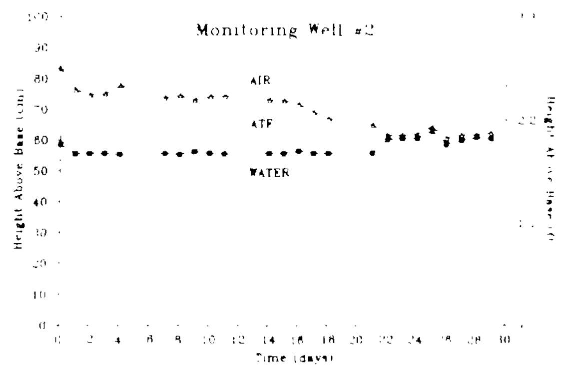


Figure 9. Response of the air/ATF and ATF/water interface in a monitoring well located adjacent to the recovery well in the model aquifer.

Results from MW2 are presented in Figure 9, which shows an initial drop in the ATF/water interface as pumping started, after which the interface was maintained at an almost constant level of about 1.80 feet (0.55m) above the base of the model aquifer for the next 19 days. Then, the interface rose to 2.03 feet (0.62m), where it remained until the end of the study. The sudden rise in the interface occurred after standing ATF in the monitoring well was pumped out. The standing ATF in the monitoring wells was removed at least once each week to make sure that the ATF in the monitoring well was hydraulically connected to ATF in the medium. After the ATF was removed on day 22, it recovered only slightly, indicating that most of the free ATF had been pumped out.

The ATF/air interface and the thickness of the ATF column in the monitoring well decreased steadily with pumping. After 23 days of pumping, only a thin layer of ATF remained in the monitoring well. At this stage during the recovery process, not only was free ATF pumped out, but also ATF from the ATF fringe zone was drained and recovered. Even in the absence of a zone of free ATF, a fully developed ATF fringe can lead to a significant column of ATF in the monitoring well. When the thickness of the zone of free ATF in the porous medium is zero, the ATF thickness in the monitoring well is determined only by capillary forces and fluid densities. The ratio of the ATF thickness in the well to that in the adjacent porous medium under hydrostatic conditions is described by the following equations (CONCAWE 1979, Zilliox and Muntzer 1975, Abdul et al. 1989):

$$H_c = p^{oa}/[(\rho_o - \rho_a)g] \quad (1)$$

$$H_w = p^{wo}/[(\rho_w - \rho_o)g] \quad (2)$$

$$H_w/H_c = (p^{wo}/p^{oa})[(\rho_o - \rho_a)/(\rho_w - \rho_o)] \quad (3)$$

where,

H_c = thickness of the ATF capillary fringe

H_w = thickness of the ATF column in the well

p = capillary pressure

ρ = fluid density

g = gravitational constant

a,o,w = air, oil, and water, respectively.

For $p^{wo} = p^{oa}$, ρ_o = 54 lb/ft³ (0.869 g/cc), a fully developed ATF fringe (H_c = 0.26 feet; 0.08m), and only a thin layer of ATF in the medium, the calculated thickness of ATF in the well is 1.73 feet (0.53m). Observe that this thickness is smaller than the maximum values observed in the monitoring wells during the accumulation of ATF in the water-table zone, but is larger than the values in MW1 (0.81 feet; 0.25m) and MW2 (1.30 feet; 0.40m) just prior to the start of pumping.

The ATF recovery rate and cumulative ATF vs. pumping time are shown in Figure 10. During the first day of pumping, the ATF recovery rate decreased rapidly from more than 0.0159 gal/hr (1 mL/min) to less than 0.00159 gal/hr (0.1 mL/min). The rate then increased to about 0.004 gal/min (0.25 mL/min) during the next few days and then followed a trend of decreasing rate with continued pumping. This trend of decreasing recovery rate follows a trend of decreasing height in the air/ATF interface in the monitoring well and decreasing thickness of the product layer adjacent to the recovery well (see Figure 9).

At the start of pumping, about 0.13 gallons (500mL) of ATF was in the 2-inch (5.08cm) I.D. recovery well, which accounts for the initial high recovery rate followed by the rapid decrease in recovery rate as that volume was being depleted. The cumulative ATF recovered from the model aquifer increased steadily during the 31 days of pumping by which time 1.71 gallons (6.47L) of ATF had been pumped out. Intermittent skimming from the recovery well for another 30 days recovered another 0.14 gallon (0.53L) of ATF, giving a total recovered volume of ATF of 1.84 gallons (6.96L), or 61 percent of the original spill volume.

As discussed previously, about 1.96 gallons (7.42L) of ATF was contained in the zone of free product and the capillary zone, of which an estimated 1.37 gallons (5.19L) could be drained and recovered by pumping. An additional 0.13 gallons (0.49L) of ATF initially stored in the wells, was also recovered, giving a total recoverable volume of 1.50 gallons (5.68L). The actual amount of ATF recovered exceeded the predicted volume by 0.34 gallons (1.29L), demonstrating that the

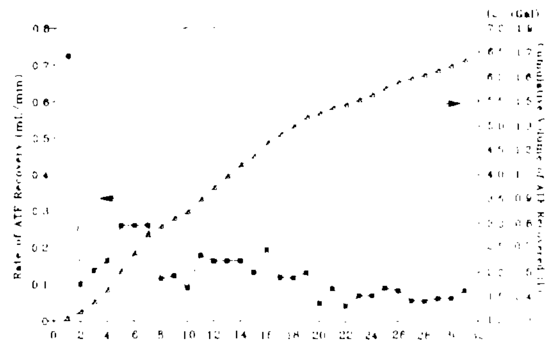


Figure 10. Recovery of ATF from the laboratory model aquifer.

recovery system performed effectively. Several factors could account for this excess volume of ATF, including underestimation of the lateral and vertical extent of the free ATF and ATF fringe zones, drainage of ATF from the funicular zone, overestimation of the residual volume of ATF, and uncertainties in quantifying the volume of ATF in the presence of ATF/water/air emulsions. Nonetheless, the results demonstrate that the new pumping strategy successfully recovered most of the drainable ATF from the model aquifer.

By maintaining the water-table drawdown at the initial position of the ATF/water interface, further spread of the ATF into the ground water zone and reduction of the recoverable volume of ATF were minimized. In addition, by maintaining a column of ATF in the recovery well in contact with the ATF layer in the porous medium, the ATF flow to the well was maintained during pumping, and the residual volume of ATF remaining trapped in the porous medium was minimized.

ATF Recovery at a Field Site

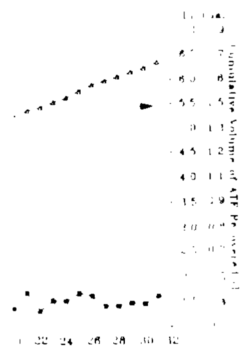
Five ATF recovery systems were installed at the field site and have been in operation for more than 770 days. Each system consists of a combination well (recovery well) and a monitoring well, which is located within a radius of 10 feet (3.05m) of the combination well. Each combination well is equipped with two air-lift pumps, a product recovery pump and a water-table drawdown pump. Product or water pumping at each recovery location is independently and automatically controlled to maintain preselected pumping conditions. Because the data from the five recovery systems are similar in trend, only the results from locations 24 and 3 will be presented (see Figure 11). Recovery well 24 is located near the prepumped centroid of the free ATF zone, about 300 feet (91.44m) downgradient of the ATF source. This location is under the plant and at least 200 feet (60.96m) away from the plant boundary. Recovery well 3 is located near the region of the ATF leak, and it is only about 30 feet (9.14m) from the plant boundary.

Response of air/ATF and ATF/water interfaces: Results for the air/ATF and ATF/water interfaces in MW24, located 3 feet from recovery well 24, during the first 829 days of product recovery at the site are shown in Figure 11. During the first two weeks of pumping,

the system was frequently ... rates of ATF and water ad... episode to establish the m... to maintain a layer of ATF ... maintain the ATF/water in... at its prepumped position ... ing of the system respo... response became more ... interval was increased to ... then to one month, and ... tored bimonthly. One we... sode, the standing ATF ... pumped out to allow th... conditions at the site.

The results indicate t... ATF and ATF/water inte... significantly during produ... start of pumping, the dep... monitoring well was 6.7... 3.13m), respectively, and t... ATF in the well. During ... depths to ATF ranged fr... 2.38m), the depths to wat... feet (2.80 to 3.37m), and th... toring well ranged from ... During this same period ... and water were 7.04 and ... respectively, giving an av... (1.01m) of ATF in the mo... and minimum thicknesses ... monitoring well were ass... shallowest drawdown o... respectively. Results for d... water interface from MW3 ... from recovery well 3, are ... start of pumping, the dep... MW3 were 5.92 and 7.92 ... tively, and there was 2 fee... During 772 days of pump... water in MW3 ranged fr... 2.00m) and from 6.64 to 8... tively, and the ATF thick... 0.14 to 2.01 feet (0.04 to ... average depths to ATF an... feet (1.85 to 2.30m), resp... thickness in the well was ... case for MW24, the ma... thicknesses observed in M... deepest and shallowest ... interface, respectively.

Although there were ... ing and maintaining opt... each of the five recovery ... depth to ATF, the depth to ... in the five monitoring we... well were similar over t... range of fluctuation of th... water, and the ATF thick... 13, 15, 24, and 39 were ... feet, 1.46, 1.70, 1.10, 1.85 ... 1.05, 2.36 and 2.30 feet



e laboratory model

-tively. Several factors
-ume of ATF, including
-d vertical extent of the
drainage of ATF from
-on of the residual vol-
quantifying the volume
-/water/air emulsions.
-nstrate that the new
-red most of the
...
-e drawdown at the in-
-terface, further spread
-r zone and reduction
-F were minimized. In
-n of ATF in the recov-
-F layer in the porous
-ll was maintained dur-
-ume of ATF remaining
-as minimized.

-re installed at the field
-r more than 770 days.
-ination well (recovery
-ich is located within a
-ombination well. Each
-h two air-lift pumps: a
-water-table drawdown
-nsich recovery loca-
-ily controlled to
-ditions. Because the
-are similar in trend,
-d 3 will be presented
is located near the
-TF zone, about 300
-e ATF source. This
-ast 200 feet (60.96 m)
. Recovery well 3 is
-TF leak, and it is only
plant boundary.

ATF/water interfaces:
-TF/water interfaces in
-ery well 24, during the
-y at the site are shown
-o weeks of pumping,

the system was frequently monitored and the pumping rates of ATF and water adjusted after each monitoring episode to establish the maximum ATF pumping rate, to maintain a layer of ATF in the product well, and to maintain the ATF/water interface in the saturated zone at its prepumped position. Subsequently, as understanding of the system response improved and as that response became more predictable, the monitoring interval was increased to one week, then to two weeks, then to one month, and the system is now being monitored bimonthly. One week before each monitoring episode, the standing ATF in the 41 monitoring wells is pumped out to allow the wells to adjust to the existing conditions at the site.

The results indicate that the position of both the air-ATF and ATF/water interfaces in MW24 did not change significantly during product recovery at the site. At the start of pumping, the depth to ATF and water in the monitoring well was 6.72 and 10.28 feet (2.05 and 3.13 m), respectively, and there was 3.56 feet (1.09 m) of ATF in the well. During 829 days of monitoring, the depths to ATF ranged from 6.21 to 7.81 feet (1.89 to 2.38 m), the depths to water ranged from 9.20 to 11.05 feet (2.80 to 3.37 m), and the ATF thickness in the monitoring well ranged from 1.95 to 4.31 feet (0.59 to 1.31 m). During this same period, the average depths to ATF and water were 7.04 and 10.36 feet (2.15 to 3.16 m), respectively, giving an average thickness of 3.32 feet (1.01 m) of ATF in the monitoring well. The maximum and minimum thicknesses of the ATF column in the monitoring well were associated with the deepest and shallowest drawdown of the ATF/water interface, respectively. Results for depth to the air/ATF and ATF/water interface from MW3, located about 5 feet (1.52 m) from recovery well 3, are shown in Figure 12. At the start of pumping, the depths to ATF and to water in MW3 were 5.92 and 7.92 feet (1.80 and 2.41 m), respectively, and there was 2 feet (0.61 m) of ATF in the well. During 772 days of pumping, the depths to ATF and water in MW3 ranged from 5.74 to 6.57 feet (1.75 to 2.00 m) and from 6.64 to 8.00 feet (2.02 to 2.44 m), respectively, and the ATF thickness in the well ranged from 0.14 to 2.01 feet (0.04 to 0.61 m). During this time, the average depths to ATF and to water were 6.06 and 7.54 feet (1.85 to 2.30 m), respectively, and the average ATF thickness in the well was 1.49 feet (0.45 m). As was the case for MW24, the maximum and minimum ATF thicknesses observed in MW3 were associated with the deepest and shallowest drawdown of the ATF/water interface, respectively.

Although there were unique challenges in controlling and maintaining optimum operating conditions at each of the five recovery stations, the results for the depth to ATF, the depth to water, and the ATF thickness in the five monitoring wells adjacent to each recovery well were similar over the duration of pumping. The range of fluctuation of the depth to ATF, the depth to water, and the ATF thickness for monitoring wells 3, 13, 15, 24, and 39 were 0.83, 0.98, 0.58, 1.09, and 0.82 feet; 1.46, 1.70, 1.10, 1.85, and 2.90 feet; and 1.87, 2.15, 1.05, 2.36, and 2.30 feet, respectively. These results indicate that the ATF in the medium was always in direct hydraulic connection with the recovery well; therefore, ATF isolation from the well was avoided. Further, the almost constant position of the ATF/water interface in the well suggests that ATF was not drawn deep into the saturated zone during pumping. These conditions were quite favorable for ATF recovery at the site, as will be demonstrated by results presented in the following section.

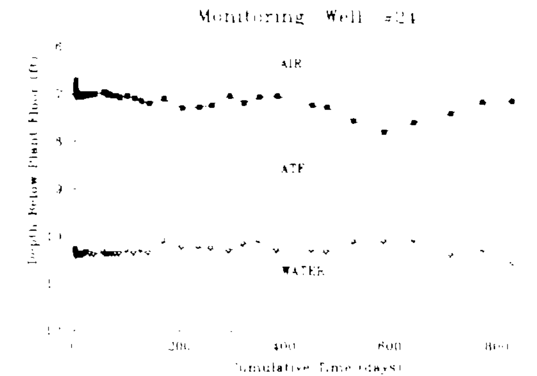


Figure 11. Response of the air/ATF and ATF/water interfaces in a monitoring well located adjacent to recovery well 24 at the field site.

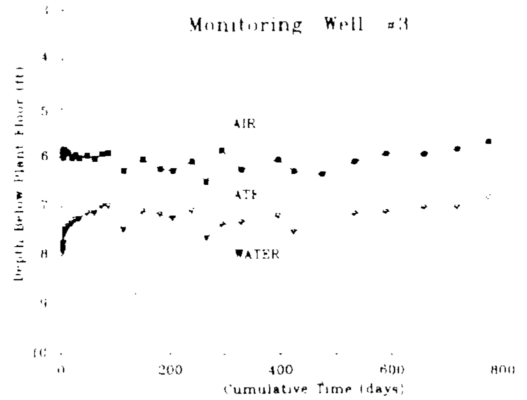


Figure 12. Response of the air/ATF and ATF/water interfaces in a monitoring well located adjacent to recovery well 3 at the field site.

Rapid fluctuation of the water table during precipitation events and reduced discharge from the water pump caused by clogging of the well screen by mineral deposits and by biomass from the biodegradation of ATF made it difficult to maintain the optimum operating conditions at the recovery wells. At the field site, all the water-table drawdown wells, water pumps, and discharge lines from these pumps developed scaling and clogging soon after the start of pumping and they had to be cleaned or replaced at least once every six months. Neither scaling nor biodegradation of ATF occurred in the presence of free ATF.

The intake of the ATF recovery pump was held fixed within the recovery well and had to be manually adjusted as the local water table position changed during recharge events or dry conditions. The recovery wells that were nearest to the outside of the plant building and to any recharge areas were more susceptible to rapid changes in the water-table position and needed more frequent monitoring and adjustment to maintain optimum recovery conditions. **Commercially available product recovery systems having product intake points that float on the product layer and automatically adjust with any fluctuation of the water table would reduce the frequency of monitoring needed at product recovery sites.**

Recovery of ATF: The ATF recovery results from recovery wells 24 and 3 are shown in Figures 13 and 14, respectively, as rate of ATF recovery and cumulative ATF recovered vs. time since pumping started. The results show a very rapid decrease in the ATF recovery rate during the first day of pumping, when the standing volume of ATF in the 4-inch I.D. (10.16cm) outer well of the combination well was being removed; thereafter, the recovery rate decreased gradually with continued pumping. At the start of pumping of recovery well 24, ATF was removed at 0.161 gal/min (610 mL/min) and water was removed at 0.872 gal/min (3.3 L/min); 829 days later, ATF was being pumped out at 0.011 gal/min (42 mL/min) and water at 0.185 gal/min (0.7 L/min). During this time, the rate for ATF recovery ranged from 0.161 to 0.005 gal/min (610 to 20 mL/min), the rate for water recovery ranged from 0.872 to 0.058 gal/min (3.3 to 0.22 L/min), the average ATF recovery rate was 0.025 gal/min (95 mL/min), and the average water pumping rate was 0.539 gal/min (2.04 L/min). During 829 days of pumping, the volume of ATF pumped from well 24 increased almost linearly to about 14,780 gallons (55,942 L).

At the start of pumping from recovery well 3, ATF was removed at 0.140 gal/min (530 mL/min) and water at 0.055 gal/min (0.21 L/min), and during pumping for 772 days the range of ATF and water removal rates were from 0.159 to 0 gal/min (600 to 0 mL/min) and from 0.806 to 0.042 gal/min (3.05 to 0.16 L/min), respectively. At the end of the study, the recovery rates were almost zero for ATF and 0.370 gal/min (1.4 L/min) for water. The average pumping rates were 0.062 gal/min (236 mL/min) for ATF and 0.206 gal/min (0.78 L/min) for water. Recovery well 3 is in a highly conductive zone that was previously excavated and backfilled with sand. This may explain the high ATF flow rate and recovery from this location. About 14,688 gallons (55,954 L) of ATF was recovered from recovery well 3.

The average pumping rates of ATF and water from recovery wells 3, 13, 15, 24, and 39 during the study are 0.062 (235.8), 0.026 (100.2), 0.006 (24.1), 0.025 (95.0), and 0.016 (59.6) gal/min (mL/min), and 0.206 (0.78), 0.177 (0.67), 0.028 (0.107), 0.539 (2.04), and 0.425 (1.61) gal/min (L/min), respectively. By the end of the study, more than 770 days since the start of pumping, the recovery rates for ATF for the wells in the order listed previously were 0, 0.013 (51), 0.002 (8), 0.011 (42), and 0.004 (17) gal/min (mL/min), respectively, and for water were 0.370 (1.40), 0.108 (0.41), 0.518 (1.96), 0.180 (0.68), and 0.246 (0.93) gal/min (L/min), respectively. During this period, a total of about 55,697 gallons (210,813 L) of ATF was pumped from the five recovery wells at an

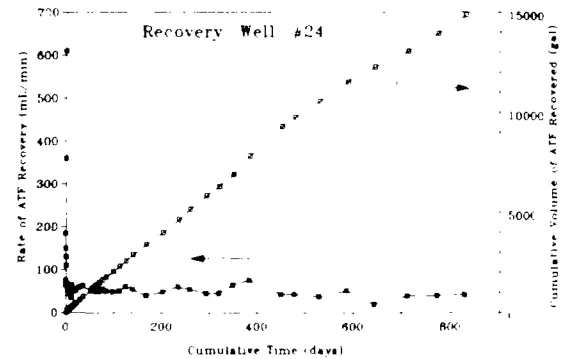


Figure 13. Recovery of ATF from well 24 at the contaminated field site.

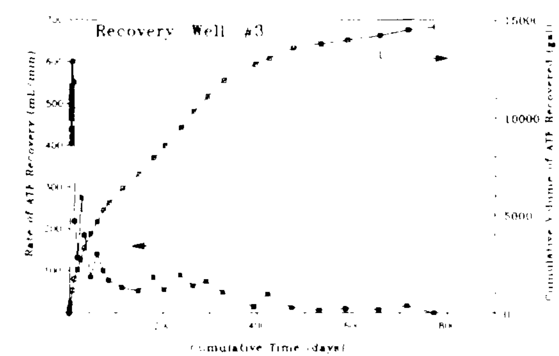


Figure 14. Recovery of ATF from well 3 at the contaminated field site.

average rate of 0.145 gal/min (550 mL/min). The volume of ATF recovered from recovery wells 3, 13, 15, 24, and 39 was 14,688 (55,594), 15,017 (56,839), 4944 (18,713), 14,787 (55,969), and 6259 (23,690)) gallons (L), respectively.

At the start of ATF recovery, the discharge from the product pump contained almost 100 percent ATF. As pumping continued, however, the amount of water in the product line increased. At first, the water was dispersed or trapped in the ATF, but with time, as the fraction of water in the product increased, the water and ATF were discharged from the product line as separate slugs. These observations are consistent with those from the laboratory study. In the case of recovery well 3, it is difficult to continue to maintain a steady discharge of ATF as a separate phase by the method being used at the site. However, with the product pump turned off for a few days, **ATF accumulated in the region of the water-table drawdown cone, but this small volume of ATF was typically pumped out in a short time after the product pump was turned back on.**

The maximum ATF thickness in the monitoring wells immediately next to the recovery wells occurred when the ATF/water interface was approximately at the deepest level, while the minimum ATF thickness occurred when the ATF/water interface was approximately the shallowest. **It is for this reason that a common practice used in product recovery is to create a deep drawdown cone to collect the product in the region around the well from where it could be readily pumped to the**

surface. However, the disadv
include the further spread of
ground water system and the
of the product that would be
a result of residual retention
ous medium. While the app
maintained a steady flow of
restricted the ATF to the reg
water system that was alread

While maintaining a sh
would have the positive eff
vertical spread of petroleum
the recoverable volume of
associated negative effect
ence of the recovery well
limitation would depend
properties.

Effect of pumping on the
ness of the vertical column of
wells at the site was measur
(more than 700 days since
was used to calculate the co
of ATF in the contiguous po
equations (Abdul et al. 198
tion (the results are shown

$H_m = H_w - H$

$H_c = p^{wo}/(\rho_w - \rho_o)g)$

where H_c is the thickness of
base of the ATF-saturated
ters are as previously defin
pressure was measured in
(Abdul 1988), and an av
(6.43cm) of ATF was used
measured value of 54 lb/ft
the specific gravity of ATF

The calculated values of
medium were mapped out
tion, contours of equal th
ure 15). The volume of AT
equal to the area between th
thickness of the ATF layer w
the fraction of the pore vo
fraction of the pore volum
porosity (ε) minus the fracti
pied by residual levels of
for the total volume of A
described by the following

$V = (\varepsilon - \theta_{rw}) \Sigma (A$

where A_i is the area betwe
and h_m is the average ATF
lines. For measured value
the volume of free ATF
approximately 87,000 gall
start of pumping, the volum
ATF was 133,000 gallons
calculations, 46,000 gall

surface. However, the disadvantages of that approach include the further spread of the product deep into the ground water system and the reduction in the volume of the product that would be available for recovery as a result of residual retention of the product by the porous medium. While the approach used in this study maintained a steady flow of ATF to the well, it also restricted the ATF to the region of the soil and ground water system that was already contaminated.

While maintaining a shallow water-table drawdown would have the positive effect of minimizing the further vertical spread of petroleum product and of maximizing the recoverable volume of product, it may also have an associated negative effect of limiting the zone of influence of the recovery well. The extent of this potential limitation would depend on the site hydrogeologic properties.

Effect of pumping on the free ATF zone: The thickness of the vertical column of ATF in the 41 monitoring wells at the site was measured at the end of this study (more than 700 days since the start of pumping), and was used to calculate the corresponding thickness (H_m) of ATF in the contiguous porous medium. The following equations (Abdul et al. 1989) were used in the calculation (the results are shown in Figure 15):

$$H_m = H_w - H_c \tag{4}$$

$$H_c = p^{wo}/\{(\rho_w - \rho_o)g\} \tag{5}$$

where H_c is the thickness of ATF in the well below the base of the ATF-saturated zone, and the other parameters are as previously defined. The ATF/water capillary pressure was measured in laboratory experiments (Abdul 1988), and an average value of 2.53 inches (6.43cm) of ATF was used in the calculations, while a measured value of 54 lb/ft^3 (0.869 g/cm^3) was used for the specific gravity of ATF.

The calculated values of ATF thickness in the porous medium were mapped out and, using linear interpolation, contours of equal thicknesses were drawn (Figure 15). The volume of ATF between two contours is equal to the area between the contours times the average thickness of the ATF layer within the two contours times the fraction of the pore volume occupied by ATF. The fraction of the pore volume occupied by ATF is the porosity (ϵ) minus the fraction of the total volume occupied by residual levels of water (θ_{rw}). This calculation for the total volume of ATF in the zone of ATF is described by the following relationship:

$$V = (\epsilon - \theta_{rw})\ \Sigma^i\ (A_i \times h_{mi}) \tag{6}$$

where A_i is the area between two adjacent contour lines and h_{mi} is the average ATF thickness for the two contour lines. For measured values of $\epsilon = 0.4$ and $\theta_{rw} = 0.07$, the volume of free ATF remaining in the subsurface is approximately 87,000 gallons (329,295L). Before the start of pumping, the volume of ATF in the zone of free ATF was 133,000 gallons (503,405L). Based on these calculations, 46,000 gallons (174,110L) of ATF was

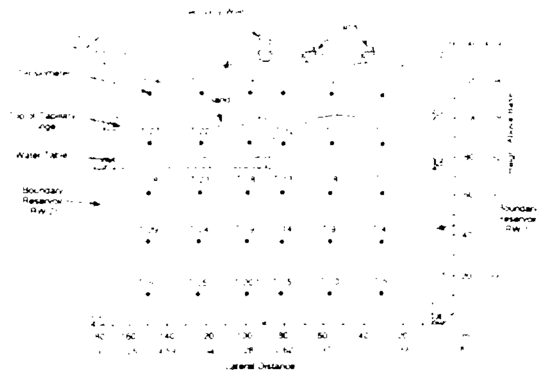


Figure 15. Lateral spread of ATF and contours of ATF thickness (feet) in the porous medium 800 days since the start of product recovery.

recovered, which compares favorably with the measured recovered volume of 55,700 gallons (210,825L). As was previously reported (Abdul et al. 1990) the uncertainty in the calculated values is ± 21,000 gallons (79,485L); therefore, the difference between the measured and calculated volume of ATF removed by pumping is within the expected range of uncertainty.

Comparison of the results in Figures 1 and 15 indicates that the ATF plume has changed significantly as a result of product recovery at the site. The maximum thickness of the free ATF layer has been reduced from a prepumped thickness of 2.6 feet (0.79m) to a value of 1.5 feet (0.46m). In addition, the plume is now divided into two main zones, one in the area of recovery well 24, where the original centroid of the plume was located, and the other in the area of well 10 sandwiched between recovery wells 3 and 15. To improve the effectiveness of ATF recovery at the site, two additional pumping stations are being installed at the current locations of well 10 and well 30 and in proximity to the two centroids of the current ATF plume (see Figure 15).

An obvious question that could be asked is how much of the ATF from the field site could be recovered by pumping. While most of the drainable ATF was recovered from the laboratory model aquifer, resulting in the removal of 61 percent of the spill volume and an equivalent residual saturation of 16 percent ATF remaining in the contaminated zone, the equivalent residual saturation for the field site is difficult to predict because of the heterogeneity in the hydrogeologic properties of the site and uncertainties in the vertical and lateral boundaries of the contaminated zone. The level of residual saturation can vary over a wide range, even in relatively simple laboratory experimental systems, because the extent of residual saturation depends on several properties of the medium and fluid, including particle size and size distribution, porosity, surface tension, fluid density, and contact angle. Kia and Abdul (1990) reported the residual retention of diesel fuel and ATF to vary from 8 to 32 percent in small funnels of sand, while Hoag and Marley (1986) found residual retention of 12 to 60 percent for gasoline in packed columns of sandy material. For field sites, which are more complex and heterogeneous than laboratory experimental systems, it would not be surprising to find even higher levels of residual retention. Nonetheless, more than 42 percent of the estimated spill volume of ATF from the free ATF zone at the field site has already been recovered (27 percent of the total volume).

Conclusions

A pumping strategy has been developed to maximize the recovery of viscous oils from soil and ground water systems. That system uses two recovery pumps: one in the layer of oil and the other extending into the saturated zone. Oil is pumped from the system at a rate maximizing the oil recovery, while maintaining a layer of oil in the recovery well and maintaining continuity between the oil in the soil with that in the recovery well. Ground water is pumped out at a rate to maintain the initially depressed oil/water interface at its prepumped position to prevent the further spread of oil into the saturated zone and to prevent a reduction in the volume of recoverable oil. This pumping strategy was tested in a laboratory model aquifer, which was contaminated with ATF to create a free ATF zone that displaced the water table into the saturated zone. Five recovery wells were installed at a 64,000-ft^2 site contaminated with about 208,000 gallons of ATF. Most of the recoverable ATF was pumped from the laboratory system, while more than 56,000 gallons of ATF is already recovered from the field site. This recovery system was successfully evaluated, it is being used to clean up the free ATF at the field site, and it could be useful at other oil-contaminated sites, particularly for the recovery of viscous oils.

Acknowledgment

The following staff members were helpful in providing assistance with the laboratory and field studies and freely gave their time to discuss different aspects of these studies: Gene Fincham, Thomas Gibson, Julie Smith, Sheila Kia, Ronald Williams, James Chan, Marilyn Smith, and Rolf Alexis.

Biographical Sketch

Abdul S. Abdul received his Ph.D. in contaminant hydrogeology from the Institute of Ground Water Research, Department of Earth Sciences, University of Waterloo, Ontario, Canada, in 1985. He has been a member of the Environmental Science Department in General Motors Research Laboratories (Warren, MI 48090-9005) since 1985, where he is now research manager of the Groundwater Decontamination Section. His major interests include the movement of immiscible fluids and reactive solutes through hydrogeologic materials, and the development of technologies based on physical, chemical, and biological processes to clean up contaminated soil and ground water systems.

References

Abdul, A.S., T.L. Gibson, and S.F. Kia. 1990. Contamination of soil and groundwater by automatic transmission fluid: site description and problem assessment. *Journal of Hydrology*, v. 121, p. 133.

Abdul, A.S., S.F. Kia, and T.L. Gibson. 1989. Limitations of monitoring wells for the detection and quantification of light petroleum products in soils and aquifers. *Ground Water Monitoring Review*, v. 9, no. 2, pp. 90–99.

Abdul, A.S. 1988. Migration of petroleum products through sandy hydrogeologic systems. *Ground Water Monitoring Review*, v. 8, no. 4, pp. 73–81.

CONCAWE. 1979. Protection of groundwater from oil pollution. CONCAWE Report No. 3/79, CONCAWE, The Hague, Netherlands, 61 pp.

Farr, A.M., R.J. Houghtalen, and D.B. McWhorter. 1990. Volume estimation of light nonaqueous phase liquids in porous media. *Ground Water*, v. 28, pp. 48–56.

Freeze, R.A. and J.A. Cherry. 1979. *Groundwater*. Prentice-Hall Inc., Englewood Cliffs, New Jersey.

Hoag, G.E. and M.C. Marley. 1986. Gasoline residual saturation in unsaturated uniform aquifer material. *Journal of Environmental Engineering*, ASCE, v. 112, no. 3; pp. 586–604.

Kia, S.F. and A.S. Abdul. 1990. Retention of diesel fuel in aquifer material. *Journal of Hydraulic Engineering*, v. 116, no. 7, pp. 881–894.

Kruseman, G.P. and N.A. de Ridder. 1970. Analysis and evaluation of pumping test data. Intern. Inst. Land Reclamation and Improvement Bull. 11, Wageningen, The Netherlands.

Lenhard, R.J. and J.C. Parker. 1990. Estimation of free hydrocarbon volume from fluid levels in observation wells. *Ground Water*, v. 28, pp. 57–67.

Schwille, F. 1967. Petroleum contamination of the subsoil: A hydrological problem. *The Joint Problems of the Oil and Water Industries*. P. Hepple, Ed. The Institute of Petroleum, London, England, pp. 23–54.

van Dam, J. 1967. The migration of hydrocarbons in a water-bearing stratum. *The Joint Problems of the Oil and Water Industries*. P. Hepple, Ed. The Institute of Petroleum, London, England, pp. 55–96.

Zilliox, L. and P. Muntzer. 1975. Effect of hydrodynamic processes on the development of ground water pollution. *Progress in Water Technology*, v. 7, pp. 561–568.